Particle Events as a Possible Source of Large Ozone Loss during Magnetic Polarity Transitions

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Brief, Popular Summary of the Paper:

This paper concerns the possibility that very large solar proton events, which occurred during periods of the Earth's magnetic reversal, might have caused fairly substantial ozone losses in the past. Large-scale explosions on the Sun near solar maximum lead to emissions of charged particles (mainly protons and electrons) from the Sun. Occasionally the Earth is positioned in its orbit such that these solar particles interact with the Earth's magnetosphere and rain down only on the polar regions. "Solar proton events" have been used to describe these phenomena since the protons associated with these solar events cause the most atmospheric disturbance.

Solar proton events create hydrogen- and nitrogen-containing compounds, which can lead to ozone destruction in the mesosphere and upper stratosphere. The largest recorded solar particle fluxes occurred during the October 1989 solar proton event. There is some evidence that even larger events occurred in the past.

The Earth's magnetic field experiences polarity reversals at irregular intervals of ~200,000 years, and during these periods of several thousand years the magnetic field is reduced to values lower that 25% of the usual strength. The solar particles would have access to more of the Earth's area during these reversal periods, thus could potentially affect more than just the polar regions.

Several model simulations were performed in this study allowing either "polar only" or "full access" to the Earth's stratosphere by the solar particles. These simulations allowed varying degrees of solar event atmospheric input (e.g., the October 1989 event only, three times this event, and three October 1989 events in the course of ten months). The model results showed that the largest impact occurred several months after the events in summer. The ozone losses were computed to reach values of 45-50% in the polar region and rival the present-day "Antarctic ozone hole" in one of the simulations, which assumed that three October 1989 events occurred in the course of ten months during an Earth magnetic reversal period.

Particle events as a possible source of large ozone loss during magnetic polarity transitions

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The energy deposition in the mesosphere and stratosphere during large extraterrestrial charged particle precipitation events has been known for some time to contribute to ozone losses due to the formation of potential ozone destroying species like NO_x and HO_x [1,2,3]. These impacts have been measured and can be reproduced with chemistry models fairly well [4,5]. In the recent past, however, even the impact of the largest solar proton events on the total amount of ozone has been small compared to the dynamical variability of ozone, and to the anthropogenic induced impacts like the Antarctic 'ozone hole'. This is due to the shielding effect of the magnetic field. However, there is evidence that the earth's magnetic field may approach a reversal [6]. This could lead to a decrease of magnetic field strength to less than 25% of its usual value over a period of several centuries [7]. We show that with realistic estimates of 'very large' solar proton events, scenarios similar to the Antarctic 'ozone hole' of the 1990s may occur during a magnetic polarity transition.

The study is based on two assumptions. First, that during a magnetic polarity transition the shielding effect of the magnetic field decreases so that high-energetic charged particles can precipitate into the atmosphere everywhere, not only in the polar cap regions ~ 30° around the magnetic poles as today; and second, that solar activity may be considerably larger in the future than at the moment. Polarity reversals of the Earth's magnetic field have occurred at irregular intervals of ~ 200,000 years. During a period of several thousand years during the reversal process, the dipole strength of the magnetic field decreased to values lower than 25% of the usual value, and the field topology was no more dominated by its dipole components [7]. The last of these magnetic polarity transitions is now 780 ka ago, and the currently decreasing dipole moment [8] and field inhomogeneities [6] may be an indicator that another polarity transition is preparing to occur in the next millennium. During the 'space age' - the last thirty to forty years of continuous measurements of solar proton and electron fluxes from space – solar proton events with high particle fluxes have been relatively sparse, with 1 to 2 events during one solar cycle [9]. However, there is evidence from ice-core depositions of nitrate that solar activity is low at the moment, and was considerably larger for example in the second half of the 19th century [10, 11]. Evidence was found in the ice-core data for solar proton events several times larger than the largest event on a reliable satellite record so far – the October 1989 event – as well as for periods where as many as three events of the same magnitude as the October 1989 event occurred in the course of ten month [11].

Here we use a global two-dimensional photochemical and transport atmospheric model to investigate the impact of very large SPEs on total ozone, and how this may be dependent on changes in the magnetic field strength (for more information about the model, see Methods section). Four scenarios were tested with a 'normal' magnetic field: 1) a "Base" scenario with no SPEs; 2) scenario "A" where the atmospheric energy deposition is equal to the largest event on record so far, the October 1989 event; 3) scenario "B" where the atmospheric energy deposition is three times larger than the October 1989 event; and 4) scenario "C" with three events of the same magnitude as the October 1989 event in the course of ten month. The duration of the individual events was set equal to that of the October 1989 event, and scaling the values calculated for the October 1989 event provides the daily averaged atmospheric energy deposition per altitude. These scenarios were chosen to provide realistic particle energy spectra while at the same time giving an estimate for 'worst case' scenarios of extraterrestrial particle precipitation. No information is available about the maximal possible size of SPEs, as the reliable record of measurements does not extend very far into the past. Scenario "B" is based on evidence for an event several times larger than the October 1989 event found in the ice-core record for the year 1859 [11]. Scenario "C" is based on a series of three very large events found in the ice-core record in the period 1893-1896 [11]. All scenarios with a 'normal' magnetic field allow precipitation of charged particles only in the polar cap regions ~ 30° around the geomagnetic poles. An additional scenario "D" was carried out that was similar to scenario "C" with three 'October 1989' events. Scenario "D" uses the assumption that the magnetic field strength has decreased significantly, and charged particles can precipitate into the middle atmosphere everywhere. The scenarios are all listed and briefly defined in Table 1.

The change of total ozone was calculated for model scenarios "B", "C", and "D" by comparing to the "Base" scenario (see Figure 1). In all model cases, significant ozone changes are confined mainly to Polar Regions > 50°. The largest impacts of the particle events on total ozone occur several months after the first event in every case. This results from the slow downward transport of the NO_x produced during the event in the polar winter vortices. Ozone losses are largest in the northern hemisphere because the particle events occurred during northern autumn and early winter, when downward transport into the winter polar vortex is most efficient. The 'worst case' scenarios "B" and "C" show very similar values of total ozone loss. In both cases, total loss of ozone is significantly larger than for the October 1989 event even for scenarios with a normal magnetic field. However, the modelled changes of 10 % to 15 % in the polar regions are in the order of magnitude of dynamical changes, smaller than the anthropogenic-induced 'ozone hole'. For scenario "D" with a strongly reduced magnetic field, losses of total ozone reach values of 45 % to 50 %, of the order of magnitude as observed in the 1990s in the Antarctic 'ozone hole' [12]. Even though particle precipitation and the resulting NO_x formation were allowed in all latitudes in this model scenario, the ozone loss is still confined mainly to polar regions, because of the global transport patterns of the middle atmosphere: most of the NO_x is produced by the solar proton events at altitudes above 40 km, well above the region of maximum ozone concentrations at 20 to 30 km, the 'ozone layer'. Large-scale downward transport occurs only in the polar winter vortices, so enhanced values of NO_x can be transported down into the 'ozone layer' region only in polar winter and spring. Contrary to the 'ozone hole', the ozone loss is not confined to a short period after polar sunrise, but is largest in summer, when the photochemical catalytic ozone destruction cycles with NO_x species are most effective. This means also that the enhancement of UV radiation due to the ozone loss occurs in the period where it may have most effect on the biosphere.

The increasing impact of solar proton events on stratospheric ozone during polarity transitions has been investigated before [13,14]. However, these previous studies used one-dimensional models to calculate a globally averaged ozone change, and they only took into account changes directly during the solar proton events. We have shown that the largest impact on total ozone does not occur during the solar proton event, but several months later, and also, that the following ozone loss has a strong latitudinal dependency.

Methods

The model used is a composite of the two-dimensional latitude-height meteorological module THIN AIR [15] and the chemical module SLIMCAT [16]. It calculates temperature, pressure, photolysis rates, transport and the behaviour of 57 chemical species on isentropic levels with a vertical resolution of ~ 3 km and a horizontal resolution of 9.47°. Most of the energy deposition during events created ion pairs (generally an electron and a positive molecule or atom) and thus the ionisation rate for a particular event is a convenient proxy to scale NO_x and HO_x production. We use the NO_x and HO_x production as a function of atmospheric ionisation that is given in Jackman et al. [17]. For all model runs, the initialisation of chemical species was done for a pre-industrial scenario, i.e. emissions of greenhouse gases like CO_2, CH_4 and N_2O, as well as source gases of chlorine, bromine and fluorine (like CFCs, halons and so on), were set to values typical for 1850 [12]. This was done first to account for paleo-historic scenarios, second, to inhibit interference of SPE-produced NO_x with reactive chlorine, thus decreasing polar ozone loss (as, e.g., discussed in a recent study [18]). Ionisation profiles were calculated from proton flux energy spectra provided by the GOES 7 satellite instrument. For model runs with a 'normal' magnetic field analogous to the current one, ionisation profiles for every latitude were weighted by the relative area of the latitudinal belt that lies inside the polar caps. For model runs with a strongly reduced magnetic field where solar energetic particles can precipitate down into the middle atmosphere everywhere, the ionisation profiles were the same for every latitude region.

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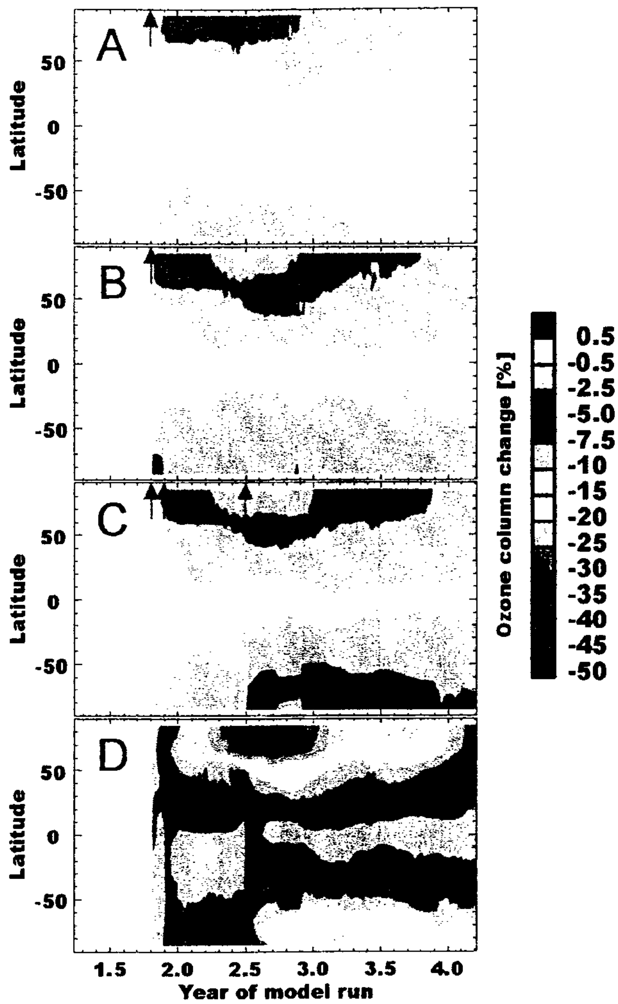
Table 1. Description of model scenarios with various solar proton event and earth's magnetic field combinations.

Scenario	Solar Proton Event(s)	Magnetic Field
Base	None	Normal
A	October 1989	Normal
B	3 times October 1989	Normal
C	October, November, and July events equal to October 1989	Normal
D	October, November, and July events equal to October 1989	Greatly reduced

Figure 1: Modelled change of total ozone as a function of latitude: A) for scenario "A", the October 1989 event; B) for scenario "B", an event three times larger than the October 1989 event happening at the same time; C) for scenario "C", a series of three events of the same magnitude as the October 1989 event within ten months; and D) for scenario "D", the same events as scenario "C" but with a strongly reduced magnetic field. The date 1.0 is the first of January of the first model year. Red arrows indicate the occurrence of solar proton events.


A
B
C
D
50
0
-50
Latitude
1.5
2.0
2.5
3.0
3.5
4.0
Year of model run
Ozone column change [%]
0.5
-0.5
-2.5
-5.0
-7.5
-10
-15
-20
-25
-30
-35
-40
-45
-50